System And Method For Inverse Multilateration

FIELD OF THE INVENTION

[0001]A system and method for determining location by using modulated signals, including code division multiple access (CDMA) and time division multiple access (TDMA) wireless communication signals, to complement or replace global positioning system (GPS) signals is disclosed. In particular, a system and method for exploiting inverse multilateration techniques to locate communication transceivers is disclosed.

BACKGROUND OF THE INVENTION

[0002]The ability to accurately determine one's location has long been a sought after goal. To that end, location determining systems have been developed. For example, GPS and other systems can be used to determine location.

[0003]One drawback associated with GPS is that, in some locations, reception of the required satellite signals is poor. Furthermore, GPS requires relatively expensive satellites and precision timing (usually with atomic clocks).

[0004]Other drawbacks of GPS systems are that they can experience geometric dilution of precision (GDOP). For example, GDOP can arise from errors propagated through the satellite signal transmission and through round-off errors in calculation.

[0005]In addition, the process of searching for and acquiring GPS signals, reading the ephemeris data for a multiplicity of satellites and computing the location of the receiver from this data can be time consuming, often requiring

several minutes. In many cases, this lengthy processing time may render the information unusable.

[0006]On the other hand, in existing cellular systems a mobile telephone's location within the cellular system can be estimated by measuring a the time difference of arrival (TDOA) of signals transmitted to or from the mobile unit. TDOA depends on a number of factors some of which include, the number of receiving locations, the number of diverse antennas at each cell site, the average distance from the transmitting unit to each of the receiving base stations, the average height of the receiving antennas, and the average antenna power gain in the direction of the transmitting unit. Some TDOA systems may require a large number of well-placed sensors in order to get a robust, enhanced accuracy measurement. Hence, there is a need for fast, relatively inexpensive, yet accurate method of determining the location of an object.

[0007]Another drawback of existing systems is that it is that the location of communication transceivers is not always accurately known. Some existing multilateration techniques rely on computations for which the known positions of transceivers is critical. Other drawbacks also exist.

SUMMARY OF THE INVENTION

[0008]Some embodiments of the present invention utilize apparatus that comprises a stand-alone receiver capable of at least a 40 - 45.15 dB processing gain (based on the short code length of 32,768). In some embodiments, the receiver may receive and digest CDMA timing information, and use it in a GPS-like computation to determine the receiver location.

[0009]In another embodiment of the present invention, there is provided a system and method, based on CDMA cellular radio standard signals. The CDMA signals may be used to provide timing data to enable position computations.

[0010] For example, in some embodiments, each cell site may transmit a synchronous signal that is correlated with GPS signals (which typically has a Rubidium or other atomic standard clock backup). Because of such synchronization, a Pilot signal from each cellular base station can be demodulated and, thereby, yield an accurate time of arrival (TOA) for a signal to a receiver. When there are multiple base stations (e.g., three base stations), transmitting to a receiver then the position of the receiver can be determined by triangulation, multilateration or other position computation technique.

[0011] One advantage of some embodiments of the invention is that they can be implemented using the existing cellular infrastructure. Typically, this infrastructure includes thousands of transmitters across the United States and other countries, many of which contain battery backup power systems, and employ numerous support personnel. In addition, at least two separate entities exist that transmit their signals at different frequencies (800 MHz and 1.9 GHz). For at least these reasons, a formidable, robust and relatively inexpensive infrastructure exists to provide a backup or supplemental pseudo-GPS system in accordance with embodiments of the invention.

[0012] In accordance with some other embodiments of the invention there is provided a system for determining the position of an object by inverse multilateration techniques. In these embodiments a mobile detection system (e.g., handheld, vehicle mounted, aircraft mounted, watercraft mounted, etc.) may be enabled to determine its own location as it moves.

[0013] Other advantages and features of the invention also exist. The following description sets forth some advantages and features of some embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014]The purpose and advantages of the present invention will be apparent to those of ordinary skill in the art from the following detailed description in conjunction with the appended drawings in which like reference characters are used to indicate like elements.

[0015]Fig. 1 is a schematic block diagram of a receiver according to embodiments of the invention.

[0016]Fig. 2 is a flow chart of a receiver location technique according to embodiments of the invention.

[0017]Fig. 3 is an illustration of a system and method to determine the location of a receiver according to embodiments of the invention.

[0018]Fig. 4 is an illustration of a system for determining the location of an object in the absence of GPS satellites and in the event that a required number of cellular base stations are not available according to some embodiments of the invention.

[0019]Fig. 5 is an illustration of a system and method for implementing inverse multilateration techniques to determine the location of transceivers in a mobile position detection system according to some embodiments of the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

[0020]The following description is intended to convey a thorough understanding of the invention by providing a number of specific embodiments and details involving the structure and operation of a novel apparatus. It should be understood, however, that the invention is not limited to these specific embodiments and details, which are provided for exemplary purposes only. It should be further understood that one possessing ordinary skill in the art, in light of known apparatuses and methods, would appreciate the use of the invention

for its intended purposes and benefits in any number of alternative embodiments, depending upon specific design and other needs.

[0021] Figure 1, is an schematic illustration of a circuit for a receiver apparatus of 200 in accordance with some embodiments of the invention. Receiver 200 may receive a signal (e.g., a CDMA pilot pseudo noise (PN) signal) from a transmitter via antenna 205. The signal may be amplified (e.g., using a low noise amplifier 210). Receiver 200 may also include in-phase mixer 215, quadrature mixer 220 and an oscillator circuit 230 for down converting the CDMA signal from the CDMA frequency to a lower frequency and then digitizing the lower frequency GPS signal into an in-phase I and quadrature phase Q digital signals. Receiver 200 may also include a variable length pseudorandom generator 265 to generate a code of suitable length. For example, some embodiments may generate a code length of 128-32,768 bits.

[0022] The in-phase portion (I) of the signal may be fed into a early 235, true 245, and late 255 correlators. Similarly, the quadrature phase (Q) portion of the signal may be fed into an early 240, true 250, and late 260 correlators.

[0023] In some embodiments, a stored reference of the variable length generator may be defined by the pilot PN sequence based on the following characteristic polynomials:

[0024]
$$PI(x) = x^{15} + x^{13} + x^9 + x^8 + x^7 + x^5 + 1$$

[0025] (for the in-phase (I) sequence)

[0026] and

[0027]
$$PQ(x) = x^{15} + x^{12} + x^{11} + x^{10} + x^6 + x^5 + x^4 + x^3 + 1$$

[0028] (for the quadrature (Q) phase sequence).

[0029] These orthogonal codes are taken from the any suitable specifications (e.g., the IS-95 specification) and can be modified for other communication system in the future.

[0030] The outputs **237, 242, 247, 252, 257 and 262** are passed onto a logic control and processing block **270**, in order for the signal to be processed.

[0031] In some embodiments, an increase in accuracy, may be obtained by oversampling the base band signals by a factor of 100 (e.g., 122.55 MHz). Doing so may increase the precision of the systems measurement of time of arrival of such signals to approximately 2.44 meters (e.g., as determined from $(3x10^8 meters/sec)/(122.55MHz)$. The amount of oversampling may be increased as the speed of available digital electronic circuits increases. Increased oversampling may be implemented to obtain greater precision in determining the location of the receiver.

[0032] Precision of the location determination may also be increased by other mechanisms. For example, precision will also increase as the chip frequency increases. It is anticipated that the WCDMA system planned for implementation in Europe within the next five years will have a chip rate of 3.84 MHz and the IS-2000 system which is in use today in the United States has provisions for a chip rate of at least 3.6864 MHz.

[0033] In some embodiments, it may be desirable to determine accurate locations for the antennas transmitting the timing signals (in CDMA the transmission antennas may be differentiated by assigned PN offsets). In general, this determination may be accomplished by obtaining a sample of transmitting antennas in a given survey area (e.g., about 10 antennas for every 1000 square miles) and then utilize location data (e.g., as provided by GPS) along with data collected from a suitable receiver (e.g., receiver 200) to determine transmitting antenna locations.

[0034] Figure 2 is a flow diagram illustrating a method for determining transmitting antenna location for some embodiments of the invention. Determining the location of a transmitting antenna may begin, as indicated at 310, with a survey of the area for which the transmitting antennas are to be located. The survey may be accomplished in any suitable manner (e.g., satellite imaging, GPS data, aerial survey or some other suitable technique). A suitable variable gain receiver (e.g., receiver 200) may be used to detect PN offset correlated with each base station antenna in the survey area. Preferably, the location of the receiver (e.g., receiver 200) may be accurately determined (e.g., from TDOA data or GPS data or some other reasonably accurate location system) as indicated at 315.

[0035] In embodiments where the survey is being performed from an aerial platform, it may be preferable for the aerial platform to circle or otherwise traverse the region of interest. For example, the aerial platform may circle and change elevation as indicated at 320. This traversal of the region of interest is performed in order to obtain data on the exact position of the transmitting object. It is preferable to obtain position data for each relevant dimension, therefore, the mobile detection platform may traverse the x, y and z planes. In an airplane (or other aerial device) one way to accomplish this traversal is to fly the airplane up in a spiral motion. In embodiments with other types of mobile platforms (e.g., land based or water based) similar traversals may be performed to collect data on the relative position of the transmitting object in reference to the detecting platform on all relevant position dimensions (e.g., x, y, and z axes).

[0036] Once this data is collected, the position of the base station transmitting antenna may be determined with an appropriate calculation as indicated at 325. For example, an inverse multilateration calculation may be performed in some embodiments.

[0037]As indicated at **330**, the process of locating base station antennas may continue as desired. In addition, the locations of base station antennas may preferably be stored in a database or other retrievable system to facilitate actual operation of the systems and methods described herein.

[0038]In embodiments of the invention where the locations of base station antenna transmitters have been located (e.g., as described above in connection with Fig. 2) or are otherwise known, a variable gain receiver (e.g., receiver **200**) may be used as a location determining device in the following manner. As shown in Figure 3, system may comprise any number of modulated signal transmitter base stations (e.g., three base stations **410(a)-410(c)** are shown in Fig. 4). The modulated signal may be transmitted in any suitable frequency range. For example, the base stations **410(a)-410(c)** may be part of a CDMA or other cellular radio-frequency system.

[0039]A suitable receiver **420** (e.g., a variable gain receiver **200** with a suitable amount of gain as described in connection with Fig. 1) may be used to determine the location of the receiver within the system **400**. The receiver **420** may comprise a hand-held device, a vehicle, aircraft or watercraft mounted device, and may be integrated into another device (e.g., a cellular phone, laptop or palm top computer, or the like).

[0040]During operation of some embodiments, the modulated signals (e.g., CDMA cellular radio standard signals) are used to provide data, part of which is an accurate timing signal, that, together with the known base station locations, can be used to determine receiver **420** location. For example, each of base stations **410(a)**, **410(b)** and **410(c)** may broadcasts a pilot signal synchronized among the base stations. Receiver **420** demodulates each pilot signal, thereby triangulating the position of the receiver based on the time difference of arrival (TDOA) of the pilot signals from each base station and to determine the location of the receiver from the known locations of the base stations **410(a)-410(c)**.

Techniques for determining receiver location, such as triangulation, TDOA, time of arrival (TOA), multilateration and the like are known and any suitable determination may be used in accordance with embodiments of the invention.

[0041] In some embodiments of the invention, the variable gain receiver (e.g., receiver **200**) may be used as a backup or supplement to an existing location determining system. For example, another embodiment shown in reference to Figure 4, illustrates a system for determining the location of an object in the absence of GPS satellites and in the event that a required number of cellular base stations are not available. System **500**, may utilize CDMA signals in conjunction with ground-based transmitters known as pseudolites (or pseudo satellites) that broadcast GPS-like signals from terrestrial locations. An entity, such as an aircraft **515** (or a vehicle, watercraft, handheld receiver, etc.), typically employs a GPS satellite navigation system (e.g., including signals transmitted from GPS satellites **510** with only one satellite shown for ease of illustration) in order to determine its position coordinates. In the event of the loss of GPS signals due to the lack of line of sight or any other such factors, aircraft **515**, which may comprise a variable gain receiver (e.g., receiver **200**) receives signals from pseudolites **520, 525** and **530** that transmit GPS-like signals that may be utilized to determine the position of the aircraft **515**. The timing reference for these pseudolites **520, 525** and **530** may be derived from the CDMA signal produced by cellular base stations located nearby (not shown). For example, GPS receiver **525** may be modified to consider the ground based pseudolites as satellites and different Gold (PN) codes may be assigned so that their transmissions would not interfere with the standard GPS satellite signals. Thus, the CDMA signal in conjunction with the pseudolite signals may be used to determine the location of the aircraft **515** (or other receiver).

[0042] In another embodiment of the present invention, and in reference to Figure 5, the location of a mobile position detection system maybe determined using an inverse multilateration method. As shown in Figure 5, the method of inverse

multilateration may be accomplished in a system comprising a ground-based transmitter **2605** that transmits a pulse at regular intervals, and a detector (e.g., a receiver mounted in an airborne platform **2610** or the like). The ground-based transmitter **2605**, transmits a pulse at time $t_{xmt\ in}$, and the pulse is received by the airborne platform **2610** at time t_{in}.

[0043] The subsequent pulse is transmitted by the ground-based transmitting sensor **2605** at time $t_{xmt\ in+1}$, and the repetition time between adjacent pulses may be calculated by:

[0044] $$t_{xmt\ in+1} - t_{xmt\ in} = Dp$$

[0045] or $$t_{xmt\ in} = (\ in - 1\ )Dp + t_{xmt\ 1}.$$

[0046] The slant range **2615** from the ground-based transmitting sensor to the airborne platform **2610** at each moment of signal interception maybe calculated by:

[0047] $$Sr_{in} = C\ (\ t_{xmt\ in} - t_{\ in}\ ),$$

[0048] where, $$in = 1, ..., Ns\ and,$$

[0049] C is the speed of light, or propagation speed.

[0050] If the position of the ground-based transmitter **2605** is represented by $\vec{P}_{sensor} = [x_{sensor}\ y_{sensor}\ z_{sensor}]^T$, the slant range between the ground-based transmitter **2605** and the airborne platform **2610** at time t_{in} may be calculated by $Sr_{in} = \left\| \vec{P}_{plane\ in} - \vec{P}_{sensor\ in} \right\|$.

[0051] The position vector of the ground-based transmitting sensor may be represented by $\vec{P}_{sensor} = [x_{sensor}\ y_{sensor}\ z_{sensor}]^T$ based on the time of arrival of each pulse, the repetition time of the transmit pulse and the position vector of the

airborne platform **2610** which is represented by $\vec{P}_{planein} = \begin{bmatrix} x_{planein} \\ y_{planein} \\ z_{planein} \end{bmatrix}$. The slant

range between the transmitting ground-based sensor and any airborne platform **2610** may also be calculated by

[0052] C (t_{in} - t_1),

[0053] where t_{in} is the time a transmitted signal is intercepted by an airborne platform **2610** *in* and t_1 is the time a transmitted signal is intercepted by an airborne platform **2610**. Using the notations described earlier, for *in=1,...,Ns*:

$$
\begin{aligned}
c(t_{in} - t_1) &= c(t_{in} - t_{xmt\ in} + t_{xmt\ in} - t_1) \\
&= c(t_{in} - t_{xmt\ in}) + c(t_{xmt\ in} - t_1) \\
&= c(t_{in} - t_{xmt\ in}) + c((in-1)Dp + t_{xmt\ 1} - t_1) \\
&= c(t_{in} - t_{xmt\ in}) - c(t_1 - t_{xmt\ 1}) + c(in-1)Dp \\
&= sr_{in} - sr_1 + c(in-1)Dp.
\end{aligned}
$$

[0054]

[0055] and knowing that $sr_{in} = \left\| \vec{P}_{plane\ in} - \vec{P}_{sensor} \right\|$. Combining the two slant range expressions yields

[0056] $c(t_{in} - t_1) = \left\| \vec{P}_{plane\ in} - \vec{P}_{sensor} \right\| - \left\| \vec{P}_{plane\ 1} - \vec{P}_{sensor} \right\| + c(in-1)Dp$,

[0057] or

[0058] $\left\| \vec{P}_{plane\ in} - \vec{P}_{sensor} \right\| = c(t_{in} - t_1 - (in-1)Dp) + \left\| \vec{P}_{plane\ 1} - \vec{P}_{sensor} \right\|$.

[0059] Squaring both sides gives

$$\left\|\vec{P}_{plane\ in} - \vec{P}_{sensor}\right\|^2 = \left(c(t_{in} - t_1 - (in-1)Dp) + \left\|\vec{P}_{plane\ 1} - \vec{P}_{sensor}\right\|\right)^2$$

$$\left\|\vec{P}_{plane\ in}\right\|^2 - 2\left\langle\vec{P}_{plane\ in}, \vec{P}_{sensor}\right\rangle + \left\|\vec{P}_{sensor}\right\|^2 = c^2(t_{in} - t_1 - (in-1)Dp)^2$$

[0060]
$$-2c(t_{in} - t_1 - (in-1)Dp)\left\|\vec{P}_{plane\ 1} - \vec{P}_{sensor}\right\|$$

$$+\left\|\vec{P}_{plane\ 1}\right\|^2 - 2\left\langle\vec{P}_{plane\ 1}, \vec{P}_{sensor}\right\rangle + \left\|\vec{P}_{sensor}\right\|^2$$

$$\left\|\vec{P}_{plane\ in}\right\|^2 - 2\left\langle\vec{P}_{plane\ in}, \vec{P}_{sensor}\right\rangle = c^2(t_{in} - t_1 - (in-1)Dp)^2$$

$$-2c(t_{in} - t_1 - (in-1)Dp)\left\|\vec{P}_{plane\ 1} - \vec{P}_{sensor}\right\|$$

$$+\left\|\vec{P}_{plane\ 1}\right\|^2 - 2\left\langle\vec{P}_{plane\ 1}, \vec{P}_{sensor}\right\rangle.$$

[0061] Reorganizing the equation gives

[0062]
$$\left\langle 2(\vec{P}_{plane\ in} - \vec{P}_{plane\ 1}), \vec{P}_{sensor}\right\rangle - 2c(t_{in} - t_1 - (in-1)Dp)\left\|\vec{P}_{plane\ 1} - \vec{P}_{sensor}\right\| = -c^2(t_{in} - t_1 - (in-1)Dp)^2$$

$$+\left\|\vec{P}_{plane\ in}\right\|^2 - \left\|\vec{P}_{plane\ 1}\right\|^2$$

[0063] defining a new variable $\tilde{sr}_1 = \left\|\vec{P}_{plane\ 1} - \vec{P}_{sensor}\right\|$, which will allow the equations

for $in=1,\ldots, Ns$ to be recast as a linear system of equations $A_1\vec{v}_1 = b_1$, with the

unknown vector defined as:

[0064] $\vec{v}_1 = \begin{bmatrix} x_{sensor} \\ y_{sensor} \\ z_{sensor} \\ \tilde{sr}_1 \end{bmatrix}$

[0065] and

$$A_1 = \begin{bmatrix} 2x_{plane\,2} - 2x_{plane\,1} & 2y_{plane\,2} - 2y_{plane\,1} & 2z_{plane\,2} - 2z_{plane\,1} & -2c(t_2 - t_1 - Dp) \\ \vdots & \vdots & \vdots & \vdots \\ 2x_{plane\,in} - 2x_{plane\,1} & 2y_{plane\,in} - 2y_{plane\,1} & 2z_{plane\,in} - 2z_{plane\,1} & -2c(t_{in} - t_1 - (in-1)Dp) \\ \vdots & \vdots & \vdots & \vdots \\ 2x_{plane\,Ns} - 2x_{plane\,1} & 2y_{plane\,Ns} - 2y_{plane\,1} & 2z_{plane\,Ns} - 2z_{plane\,1} & -2c(t_{Ns} - t_1 - (Ns-1)Dp) \end{bmatrix}$$

[0066]

$$b_1 = \begin{bmatrix} \left\| \vec{P}_{plane\,2} \right\|^2 - \left\| \vec{P}_{plane\,1} \right\|^2 - c^2(t_2 - t_1 - Dp)^2 \\ \vdots \\ \left\| \vec{P}_{plane\,in} \right\|^2 - \left\| \vec{P}_{plane\,1} \right\|^2 - c^2(t_{in} - t_1 - (in-1)Dp)^2 \\ \vdots \\ \left\| \vec{P}_{plane\,Ns} \right\|^2 - \left\| \vec{P}_{plane\,1} \right\|^2 - c^2(t_{Ns} - t_1 - (Ns-1)Dp)^2 \end{bmatrix}.$$

[0067] The method of least squares may be used to solve this linear system so that $\bar{v}_1 = \left(A_1^T Q^{-1} A_1 \right)^{-1} A_1^T Q^{-1} \cdot b_1$ where Q is the measurement covariance matrix nominally set as identity matrix of dimension $(Ns-1) \times (Ns-1)$.

[0068] Methods of implementing an Inverse Multilateration computation in accordance with embodiments of the invention can be summarized as follows. As the mobile detection system (e.g., airplane 2610) moves along a curve, the receiver onboard the mobile detection system collects the arrival times of the pulses from the ground-based transmitting sensor and the position of the detection system at each time of arrival. Then the position of the ground transmitter is computed by solving

[0069] $\qquad\qquad \bar{v}_1 = \left(A_1^T Q^{-1} A_1 \right)^{-1} A_1^T Q^{-1} \cdot b_1 .$

[0070] Of course, once the position of the ground transmitter is known, the relative position of the mobile detection system 2610 with respect to the transmitter may also be computed.

[0071] In another embodiment, a Monte Carlo approach may be included in the inverse multilateration technique. For example, a Monte Carlo technique may be used in order to have an added Gaussian noise error added to the time of arrival data,

[0072] $t_{in} = t\_0_{in} + N(\sigma_t)$

[0073] where, t_0_{in} is the actual time of arrival of the transmitted signal by the ground-based transmitter **2605** at the airborne platform **2610**, and $N(\sigma_t)$ is random Gaussian noise error of variance σ_t.

[0074] A simulation of the inverse multilateration technique may be applied to a three dimensional case, wherein the ground-based transmitting sensor is

positioned at $\vec{P}_{sensor} = \begin{bmatrix} 200 \\ 150 \\ 100 \end{bmatrix}$., while the airborne platform **2610** may be defined by

$\vec{P}_{plane}(t) = \begin{bmatrix} R\cos(\theta(t)) \\ R\sin(\theta(t)) \\ alt(t) \end{bmatrix}$, where $alt(t) = alt_0 + D_{alt}\sin(2\pi f_{alt}t)$ and $\theta(t) = \theta_0 + \Delta\theta.t$. In

this simulation, the airborne platform **2610** may be presumed to move in a circular, sinusoidal path and thereby maintaining reasonable diversity in all three axial directions., where *R=500m, alt₀=500m, D_{alt}=200m, f_{alt}=1/60 seconds, θ₀ =0 degrees, Δθ =400 Knots/R, Dp=4 seconds*, and the variance of the added Gaussian errors to the time of arrival data is $\sigma_t^2 = (0m/c)^2$ for case one, $(5m/c)^2$ for case two and $(30m/c)^2$ for case three. The added Gaussian errors to the airborne platform 610 position may have the variance $\sigma_x^2 = \sigma_y^2 = \sigma_z^2$ which is equal to $(0m)^2$ for case 1, $(5m)^2$ for case two and $(10m)^2$ for case three.

[0075] The invention now being fully described, it will be apparent to one of ordinary skill in the art that many changes and modifications can be made thereto without departing from the spirit or scope of the invention as set forth herein. The foregoing describes some embodiments of the invention along with a number of possible alternatives. These embodiments, however, are merely for example and the invention is not restricted thereto. It will be recognized that various

materials and modifications may be employed without departing from the invention described above, the scope of which is set forth in the following claims.